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RESEARCH MEMORANDUM

USE OF CONSTANT DIFFUSER MACH NUMBER AS A CONTROL
PARAMETER FOR VARIABLE-GEOMETRY INLETS

AT MACH NUMBERS OF 1.8 TO 2.0

By Donald P. Hearth and Bernhard H. Anderson

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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**NATIONAL ADVISORY COMMITTEE
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SUMMARY

Analysis was made to determine the feasibility of using a constant diffuser Mach number to position a translating spike for optimum inlet performance. A control system incorporating this concept was investigated on a blunt lip, translating-spike inlet at flight Mach numbers of 1.8 to 2.0 and angles of attack up to 6° . In addition, unpublished data for a two-dimensional variable ramp inlet were analyzed to determine the possible use of this same control principle for positioning a variable wedge.

When the area at the diffuser Mach number sensing station is varied properly as the spike is translated, close to optimum inlet performance will be set by the control. The same results were noted for the variable ramp inlet. When critical mass-flow ratio decreased as the spike was retracted because of excessive internal contraction, improved performance at a given engine airflow resulted from operating the inlet supercritically at a spike position more extended than that for critical operation. A constant diffuser Mach number control will set such supercritical operation if the sensing station area is varied properly.

INTRODUCTION

The need for variable geometry on supersonic inlets has been demonstrated; this geometry may consist of a bypass ahead of the engine, a translating spike, a variable angle wedge, or a variable capture area. In order to position the variable inlet feature, an automatic inlet control system is generally desirable so that close to optimum inlet performance may be maintained over a range of flight Mach numbers, ambient temperatures, and engine throttle settings. A number of control systems utilizing various inlet principles have been proposed and investigated (e.g., refs. 1 to 4).

Use of constant subsonic diffuser Mach number as a control parameter is discussed in reference 3. The control was used to actuate a bypass ahead of the engine in order to maintain close to critical inlet operation as the engine required varying airflows. The control Mach number was sensed at a constant area station ahead of the bypass. Such a system would not be directly applicable to inlets that spill excess inlet flow with a translating spike or a variable wedge. As the spike or ramp was moved to provide critical operation over a range of engine airflows, the Mach number at a constant area station would vary. However, as shown in this report, proper variation of the area at the sensing station can result in a constant Mach number that may be used as a control parameter.

Discussed herein are the principles for the design and operation of an inlet control that senses and sets a constant diffuser Mach number for close to optimum performance of variable geometry inlets. Tests were conducted at the NACA Lewis laboratory with both an exit plug and a turbojet engine on the full-scale translating-spike inlet described in reference 5. The performance of the inlet as set by a constant Mach number control is presented at free-stream Mach numbers of 1.8 to 2.0 and angles of attack up to 6° .

SYMBOLS

A	flow area, sq in.
D	drag, lb
F	thrust, lb
F_i	ideal thrust (100-percent pressure recovery), lb
M	Mach number
m	mass flow, slugs/sec
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
w	weight flow, lb/sec
$\frac{w\sqrt{\theta}}{\delta}$	corrected airflow, lb/sec
α	angle of attack, deg

- δ ratio of total pressure to NACA standard sea-level static pressure of 2116 lb/sq ft
- θ ratio of free-stream total temperature to NACA standard sea-level static temperature of 518.7° R
- θ_1 spike-position parameter (angle between diffuser axis and line joining apex of cone to cowl lip), deg
- λ second ramp angle, deg

Subscripts:

- cr critical
- in inlet
- 0 free stream
- 1 sensing station
- 2 compressor face

DIFFUSER MACH NUMBER AS INLET CONTROL PARAMETER

The use of a Mach number in the subsonic diffuser as an inlet control parameter to position a bypass ahead of a turbojet engine is discussed in reference 3. This system, which sensed the Mach number at a constant area station, could not be used to actuate a translating spike because the value of the Mach number for critical operation varied as the spike was translated.

Condition for Constant Mach Number at Control Sensing Station

If the area at the Mach number sensing station is varied properly as the spike is translated, the value of the Mach number at that station remains a constant for critical operation. Considering figure 1, continuity between stations 1 and 2

$$w_1 = w_2$$

Since

$$\frac{w\sqrt{\theta}}{\delta A} = f(M)$$

$$M_1 = f \left(\frac{w_2 \sqrt{\theta_2}}{\delta_2} \frac{P_2/P_1}{A_1} \right) \quad (1)$$

Thus, if the flow area at the sensing station A_1 changes with the inlet variable (e.g., spike translation) so that

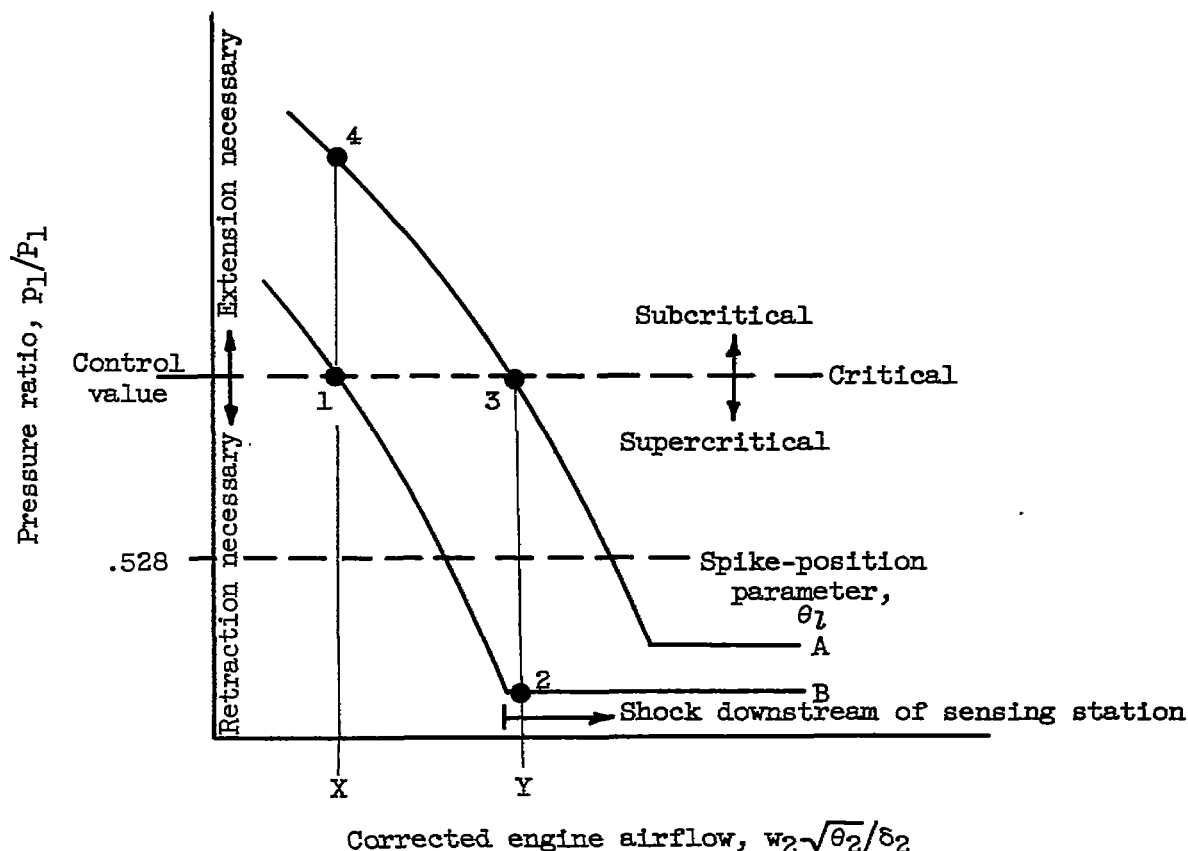
$$\frac{\left(\frac{w_2 \sqrt{\theta_2}}{\delta_2} \frac{P_2}{P_1} \right)_{cr}}{A_1} = \text{constant} \quad (2)$$

the value of the sensing station Mach number M_1 will be a constant during critical inlet operation at any given flight Mach number.

It would be necessary to schedule the value of M_1 with flight Mach number if the numerator of equation (2) were not a constant for each spike position over the flight Mach number M_0 range. Constant corrected airflow at critical operation has been noted for several inlets (e.g., refs. 4, 5, and 6) but not for others (e.g., refs. 3 and 7). The variation of total-pressure recovery P_2/P_1 with Mach number would be dependent on the location of the sensing station, the particular inlet configuration, and the range of inlet position required at each Mach number.

Principle of Operation

The Mach number is sensed by means of the ratio of static to total pressure p_1/P_1 . These quantities are measured separately, and the ratio is then determined and compared with the set value. If the measured ratio is high, the control system would call for spike extension (and vice versa). Consider the variation of the pressure ratio for a fixed inlet condition (spike-position parameter $\theta_1 = \text{constant}$). When the inlet operation is supercritical so that the inlet terminal shock is downstream of station 1, the value of p_1/P_1 is at a minimum, less than 0.528 ($M_1 > 1.0$). As the corrected airflow is reduced, p_1/P_1 will remain a constant until the shock moves upstream of station 1. The value of p_1/P_1 will continue to increase for further decreases in corrected airflow.



If equation (2) has been satisfied, p_1/P_1 will be a constant (as shown in the preceding sketch) for critical operation at various corrected airflows $w_2\sqrt{\theta_2}/\delta_2$. If the inlet is operating critically at point 1 ($\theta_l = B$ and $w_2\sqrt{\theta_2}/\delta_2 = X$) and the airflow is increased to Y (as by a decrease in ambient temperature, ref. 8), the inlet will operate supercritically at point 2 unless the spike is translated. Since p_1/P_1 would have decreased as shown, the control would call for the spike to retract (to $\theta_l = A$), and critical inlet operation would result at point 3. A decrease in corrected airflow from Y to X would result in path 341.

If there is a standing normal shock ahead of the cowl lip, the pressure signals will be the same as shown in the sketch except that the minimum value of p_1/P_1 for each θ_l might be greater than 0.528. Critical operation at various airflows still results in a constant value of p_1/P_1 .

if equation (2) is satisfied. Thus, such a control system could be used to set critical inlet operation even at low flight Mach numbers, where external shock detachment may occur. If the normal shock ahead of the cowl is due to excessive internal contraction, it still would be possible to vary A_1 so as to result in a constant value of p_1/P_1 at critical operation. However, a higher inlet performance may result if the inlet is operated supercritically. This phenomenon will be discussed later in this report.

APPARATUS AND PROCEDURE

The inlet discussed in reference 5, incorporating a diffuser Mach number control, was investigated in the Lewis 10- by 10-foot supersonic wind tunnel. A full-scale production nacelle (fig. 1) was used with both a turbojet engine and an exit plug simulating various engine airflows. The inlet had a translating spike and a blunt cowl lip. Details of the inlet, nacelle, and engine are included in reference 5.

Static pressure and total pressure were measured at the sensing station (fig. 2). The static-pressure orifice for the control was located at station 2.4, designated the sensing station. The total-pressure tube was attached to the spike and moved with spike translation as shown in figure 2. Both probes were located on the horizontal centerline. The pressures were divided and compared mechanically with the desired value in a transducer. An electrical error signal was fed into a motor that actuated the screwjack. A static to total pressure ratio of 0.585, determined from small-scale inlet tests, was built into the transducer.

The internal-flow-area distribution for the inlet is shown in figure 3. As the spike was retracted (increasing θ_1), the amount of internal contraction increased.

At each test Mach number and angle of attack, the engine corrected airflow was varied, and the control system was used to position the spike. The inlet control also was investigated during spike transients in which the spike was displaced manually and allowed to be returned by the control. No unfavorable interaction between the inlet and engine controls was obtained because of the slow movement of the screwjack actuator (about $3 \text{ sec}/10^\circ \theta_1$).

RESULTS AND DISCUSSION

Inlet Characteristics

The performance of the inlet during critical operation is summarized in figure 4. It is interesting to note that the inlet mass-flow ratio decreased for a spike retraction beyond a θ_1 of about 41.5° because of excessive internal contraction in that spike-position range. The corrected airflow delivered by the inlet at critical operation (fig. 4(c)), was a function of spike position only for the Mach number and angle-of-attack range investigated. Thus, the same value of p_1/p_1 (i.e., M_1) could result at critical operation if P_2/P_1 also were only a function of spike position (see eq. (2)) and if A_1 is varied properly.

In order for the diffuser Mach number control to operate the inlet critically, the sensing station area would have to vary as shown in equation (2). The actual area variation is compared with the required area variation in figure 5. Since the actual variation of P_2/P_1 is unknown, two limiting cases are presented: $P_2/P_1 = \text{constant}$ (fig. 5(a)), and $P_1/P_0 = \text{constant}$ (fig. 5(b)); that is, $P_2/P_1 = \text{a variable accounting for all the change in } P_2/P_0$. The area-variation comparison for the actual case is somewhere between the two limits shown in figure 5. Because of the apparent deviation of the area from that required for critical operation, the control would be expected to set supercritical operation at high values of θ_1 .

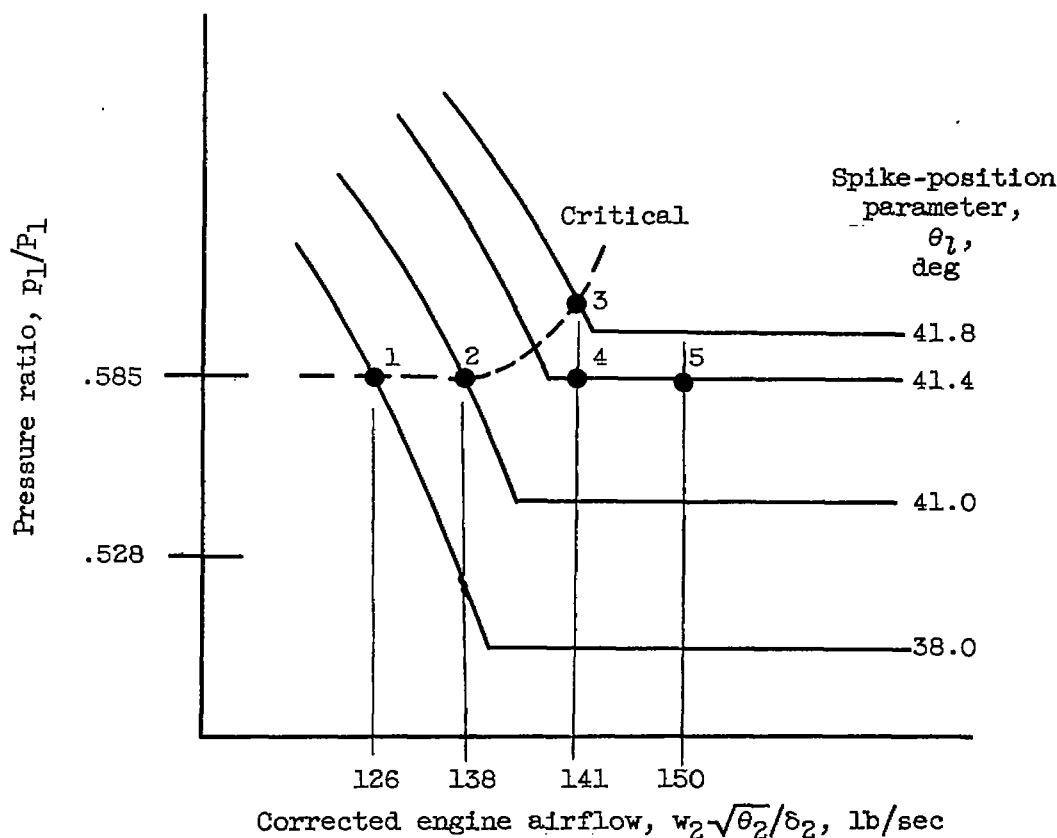
The signals used to actuate the control are presented in figure 6. These data were taken at manually set spike positions for the various engine airflows shown. Circumferential static-pressure gradients at the sensing station, due to slight misalignment of the cowl and spike, were noted during the early testing. The data presented in figure 6 and all other control data presented in the following figures were taken with very little pressure gradient at the sensing stations.

Figure 7 shows a comparison of the pressure signals measured with the full-scale inlet and those measured with the quarter-scale model of reference 9. Although data are presented for only one engine condition at Mach 1.8, similar results were noted at the other test conditions. Since the slopes of the two pressure signals are considerably different, it appears that shock boundary-layer interaction does not scale from one model to another. The data agreement near the set value (0.585) may have been coincidental, since this value of pressure ratio did not occur when the normal shock passed over the static orifice. It also should be noted that in reference 9 the total-pressure tube was mounted to the cowl in such a manner that it did not move with the spike.

Performance With Control

The steady-state inlet operation set by the control is presented in figure 8. These data are compared with an envelope of critical inlet operation. The spike position set by the control indicates that close to critical inlet operation resulted for all Mach numbers and angles of attack up to an engine airflow of about 140 pounds per second. The inlet pressure recovery was, therefore, very close to the critical value in this airflow range. At airflows in excess of 140 pounds per second, the control maintained the spike at a θ_1 of about 41.4° . Thus, the inlet operated supercritically in this airflow range.

In figure 5, the sensing station area is estimated to be greater than that required for critical operation at values of θ_1 greater than about 41° . It was noted in the previous discussion of figure 5 that the control would set supercritical operation above an engine airflow associated with critical operation at the limiting θ_1 . The following sketch illustrates what apparently happened at the high engine airflow:



At the low airflow (e.g., 126 lb/sec) critical operation at point 1 was set by the 0.585 pressure-ratio control. When the airflow was increased to 138 pounds per second, the control again set the spike so that the inlet operated critically (point 2). When the spike was retracted to the θ_1 of 41° , a normal shock occurred ahead of the cowl lip (because of internal contraction) and thus raised the minimum part of the signal curve above 0.528 (i.e., $M < 1.0$). A further increase in airflow to 141 pounds per second would require a θ_1 of 41.8° for critical operation (point 3). However, figure 5 indicates that, for a θ_1 greater than about 41° , the sensing area was too large, and the control operated the inlet supercritically. Thus, the control retracted the spike to only 41.4° , and the inlet operated at point 4 with the inlet terminal shock downstream of the sensing station. A further increase in airflow to 150 pounds per second caused the shock to move farther downstream, and the inlet operated at point 5.

Although the control set supercritical operation at the high engine airflows, the data presented in figure 8 indicate higher pressure recovery than if the spike were retracted farther to obtain critical operation. The reason for this is apparent in figure 9, wherein the inlet performance for two high airflows is shown over a range of manually set spike positions. These data are compared with an envelope of critical operation. For any given airflow, when the spike is extended beyond that for critical operation the inlet will operate supercritically. Thus, as the spike is retracted from a low θ_1 the inlet approaches critical operation. Figure 9 indicates that as θ_1 was increased for a high airflow the mass-flow ratio (which is the same as the critical value) increased up to a θ_1 of 41.5° , with a corresponding increase in the pressure recovery and thrust minus drag. However, as the spike was retracted beyond 41.5° , the mass-flow ratio began to decrease even though the inlet was still supercritical because of the excessive internal contraction of the inlet. The pressure recovery decreased at the same rate as the mass-flow ratio; the thrust minus drag decreased at a greater rate because of increasing additive drag. When the spike was positioned for critical operation, both the pressure recovery and the thrust-minus-drag values were considerably below those at a θ_1 of 41.5° . Thus, since the constant diffuser Mach number control set the spike to operate supercritically at the high airflows, the higher-than-critical inlet performance shown in figure 8 resulted.

The inlet performance as set by the control is compared in figure 10 with the peak performance possible with the fixed-cowl - translating-spike inlet configuration. Although data are presented only at Mach 2.0 and zero angle of attack, the results would be essentially the same at the other test conditions. As discussed previously, superior performance at high airflows occurred when the inlet was operated supercritically. At the lower airflows, slightly better performance resulted from slightly

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subcritical operation. The data presented in figure 10 indicate that the control positioned the spike so that very close to peak inlet performance was obtained over the entire range of engine conditions.

The preceding discussion has dealt with the application of the concept of a constant diffuser Mach number control to a translating-spike inlet. This type of control also might be applicable to variable ramp - two dimensional inlets. Unpublished data for a two dimensional - variable ramp inlet have been analyzed in the same manner as the translating-spike data of this report. Static- and total-pressure instrumentation was installed in the diffuser and, although a control was not tested, the measured pressure signals indicate how such a control would function.

Figure 11 presents the variation with ramp position of the area at the sensing station for the two-dimensional configuration; this variation agrees quite closely with that required for critical operation. Thus, it would be expected that a constant diffuser Mach number control would set close to critical inlet operation. The pressure signals measured in this test indicate that such a control, if used, would position the ramp as shown in figure 12. As expected, close to critical operation with its resulting performance would occur.

SUMMARY OF RESULTS

The following results were obtained from a controls investigation of a translating-spike inlet with internal contraction and from the analysis of unpublished data for a variable wedge inlet:

1. The use of a constant diffuser Mach number as an inlet control parameter may be applied to variable-geometry inlets if proper area variation exists.
2. A control using the constant Mach number principle was successfully operated with a translating-spike inlet. Performance at, or very near, the maximum possible propulsive thrust was obtained over the entire range even with normal shocks standing ahead of the cowl lip.
3. Unpublished data for a variable ramp inlet indicated that a control based on the constant diffuser Mach number principle would operate such an inlet satisfactorily, at least over the Mach number range investigated (1.5 to 2.0).
4. When critical inlet mass-flow ratio decreased as a spike was retracted because of excessive internal contraction, improved performance at a given engine airflow resulted by operating the inlet supercritically at a spike position more extended than the position for critical operation.

5. When an inlet had excessive internal contraction, a constant diffuser Mach number control set close to optimum inlet performance (maximum propulsive thrust) with supercritical inlet operation if the area at the sensing station was varied properly.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 9, 1957

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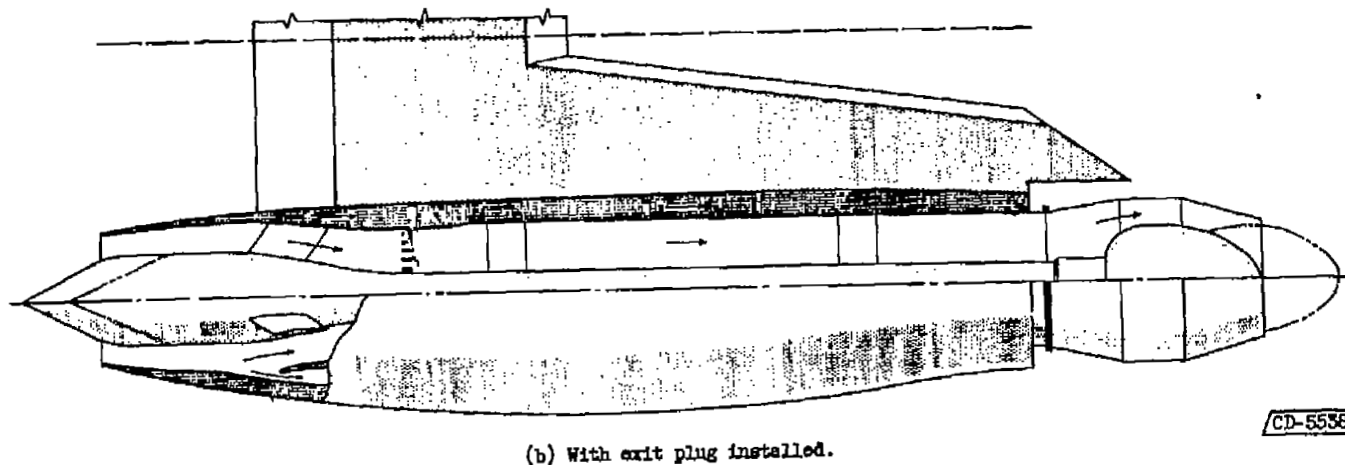
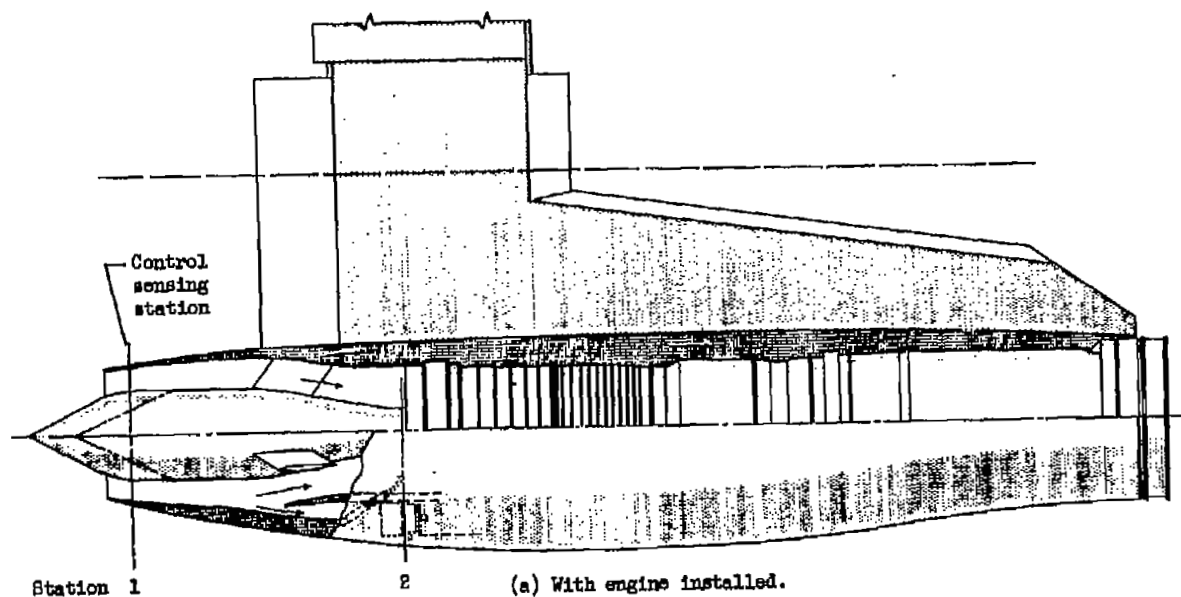


Figure 1. - Nacelle configuration.

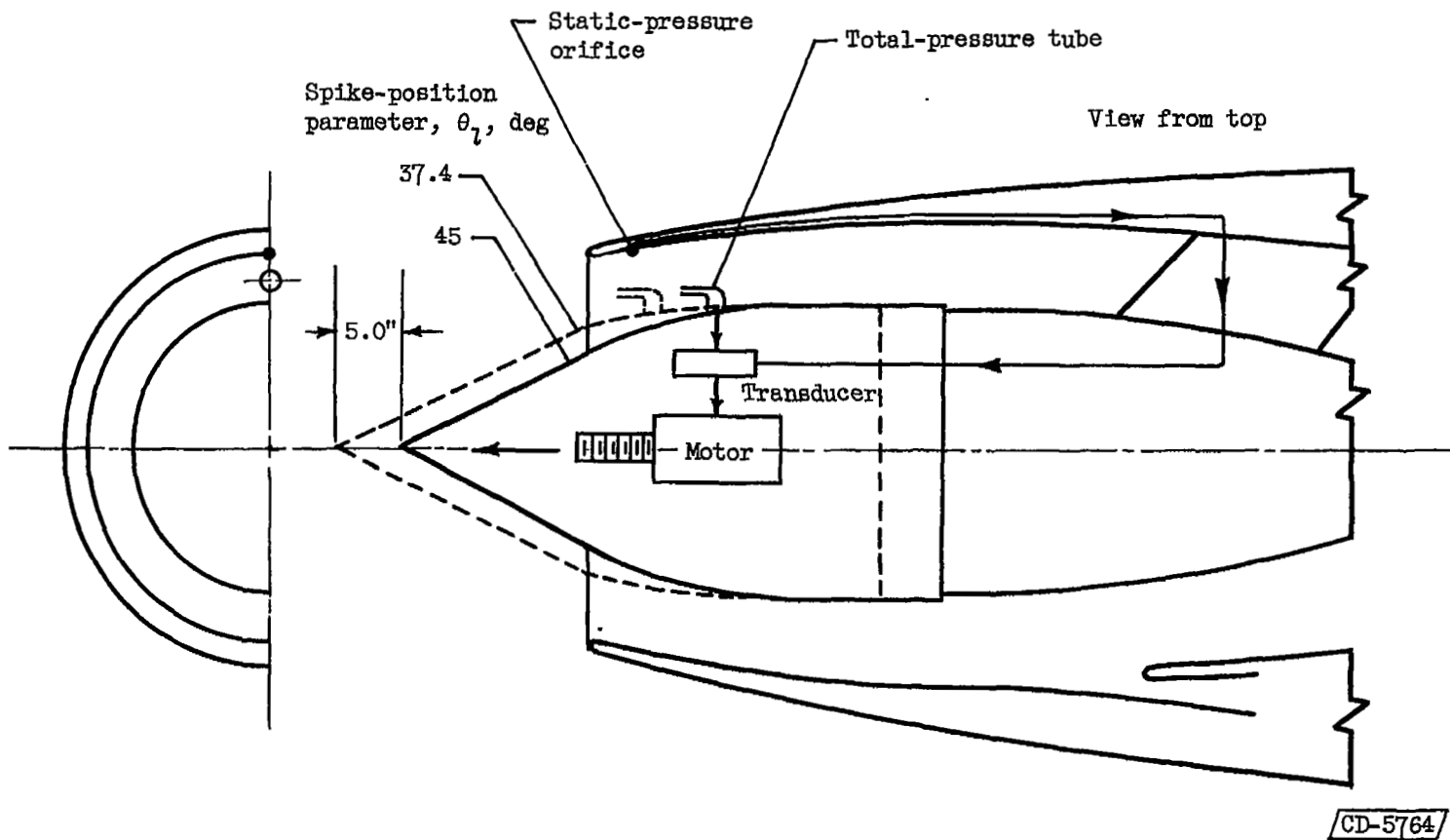


Figure 2. - Translating-spike control arrangement.

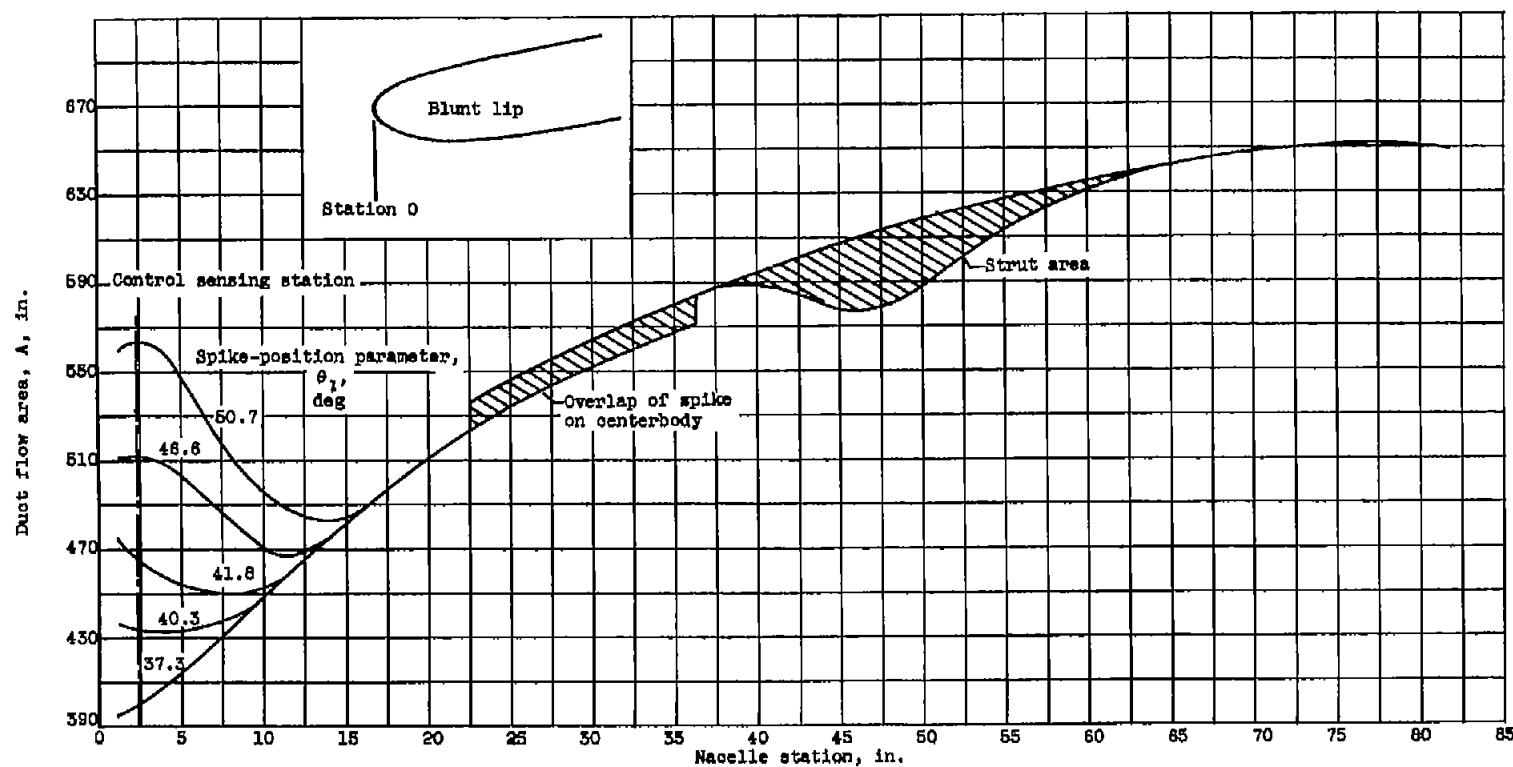
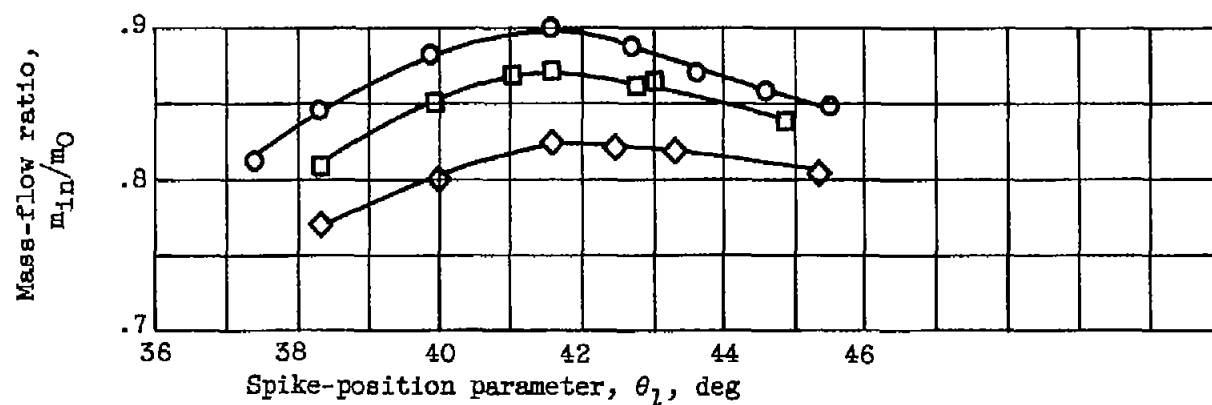


Figure 3. - Internal area distribution. (Nacelle station 0 located at vertical tangent to cowl lip.)

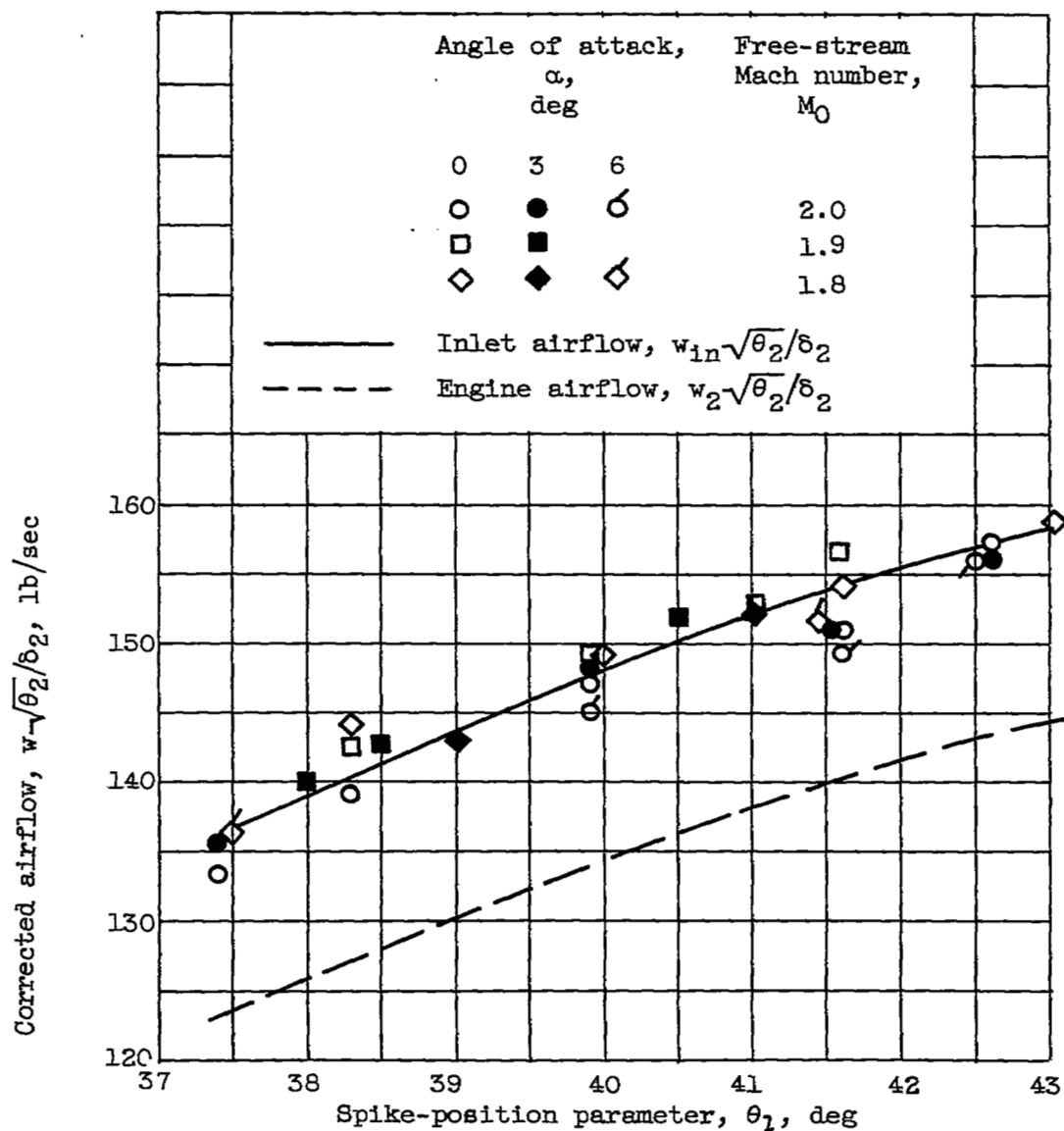


(a) Total-pressure recovery. Angle of attack, 0° .



(b) Inlet mass-flow ratio. Angle of attack, 0° .

Figure 4. - Critical inlet performance.



(c) Corrected airflow.

Figure 4. - Concluded. Critical inlet performance.

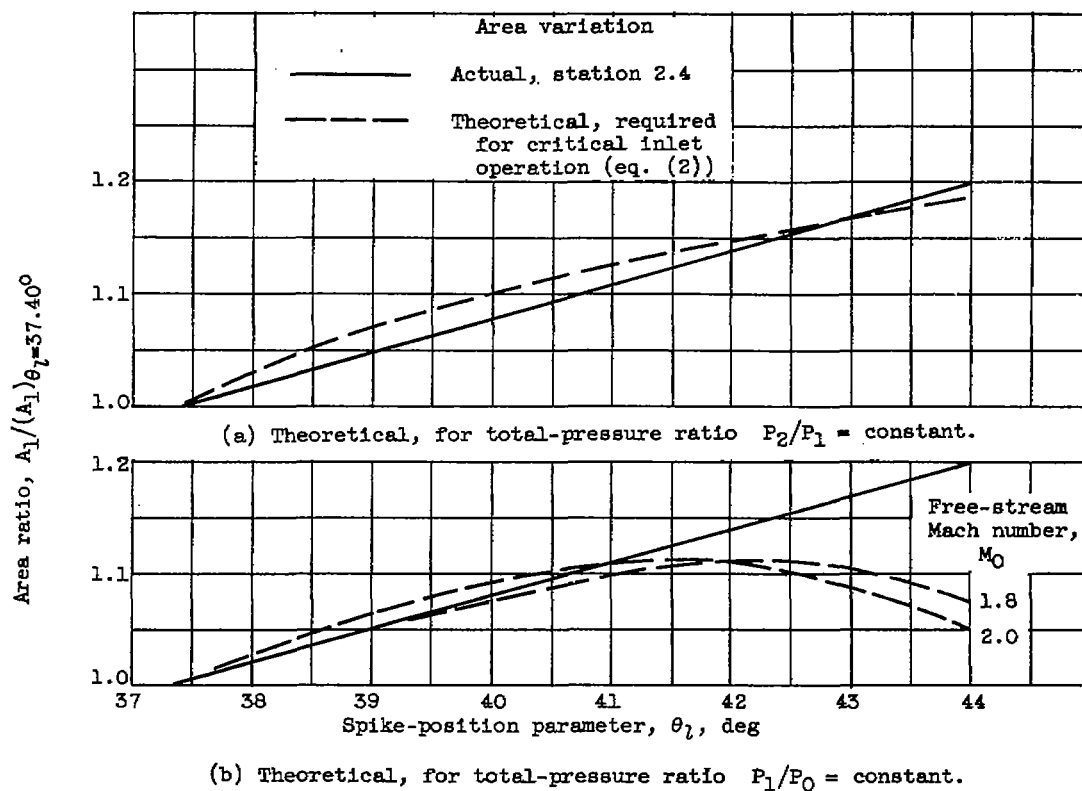


Figure 5. - Characteristics of area variation at control sensing station.

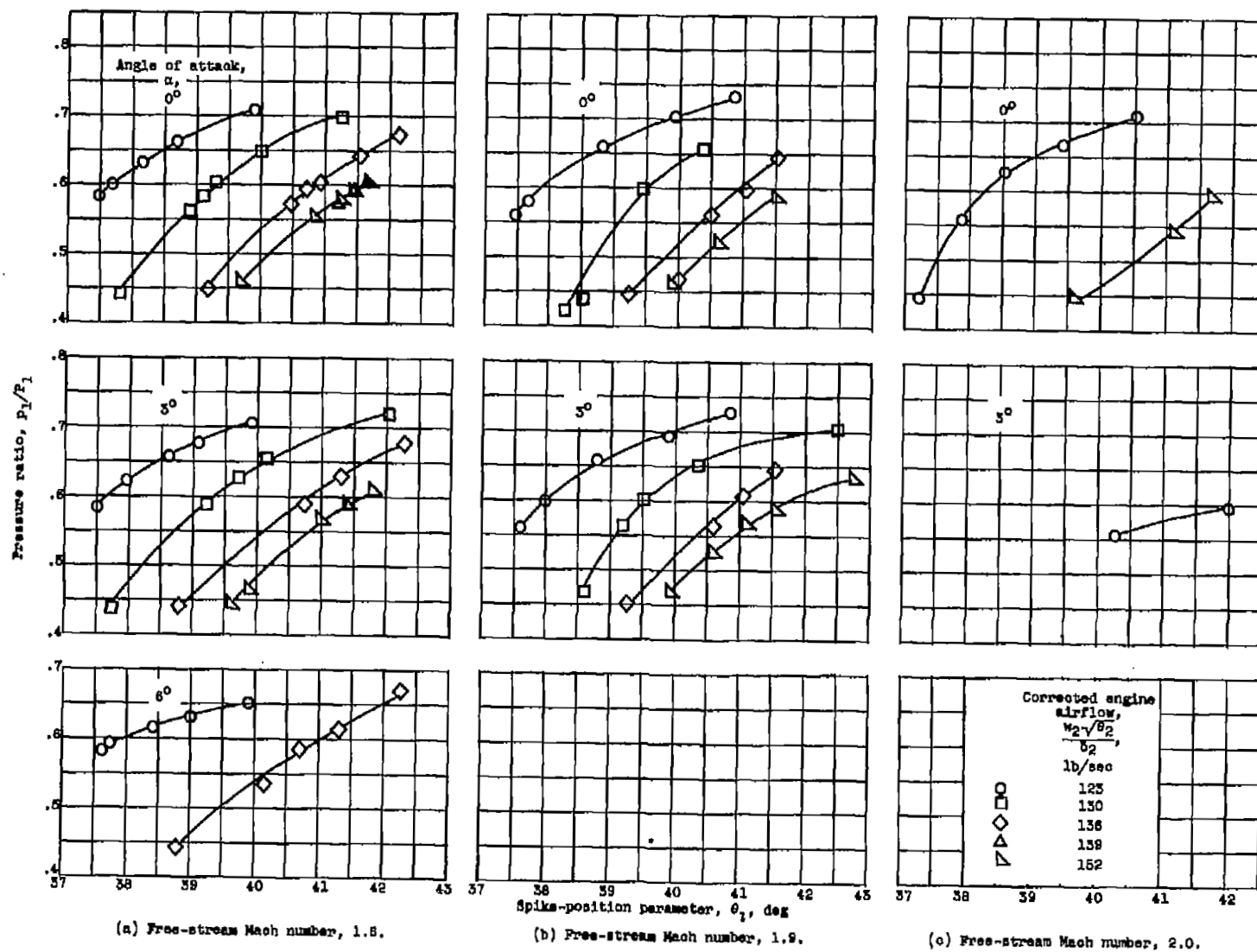


Figure 6. - Pressure-ratio control signals.

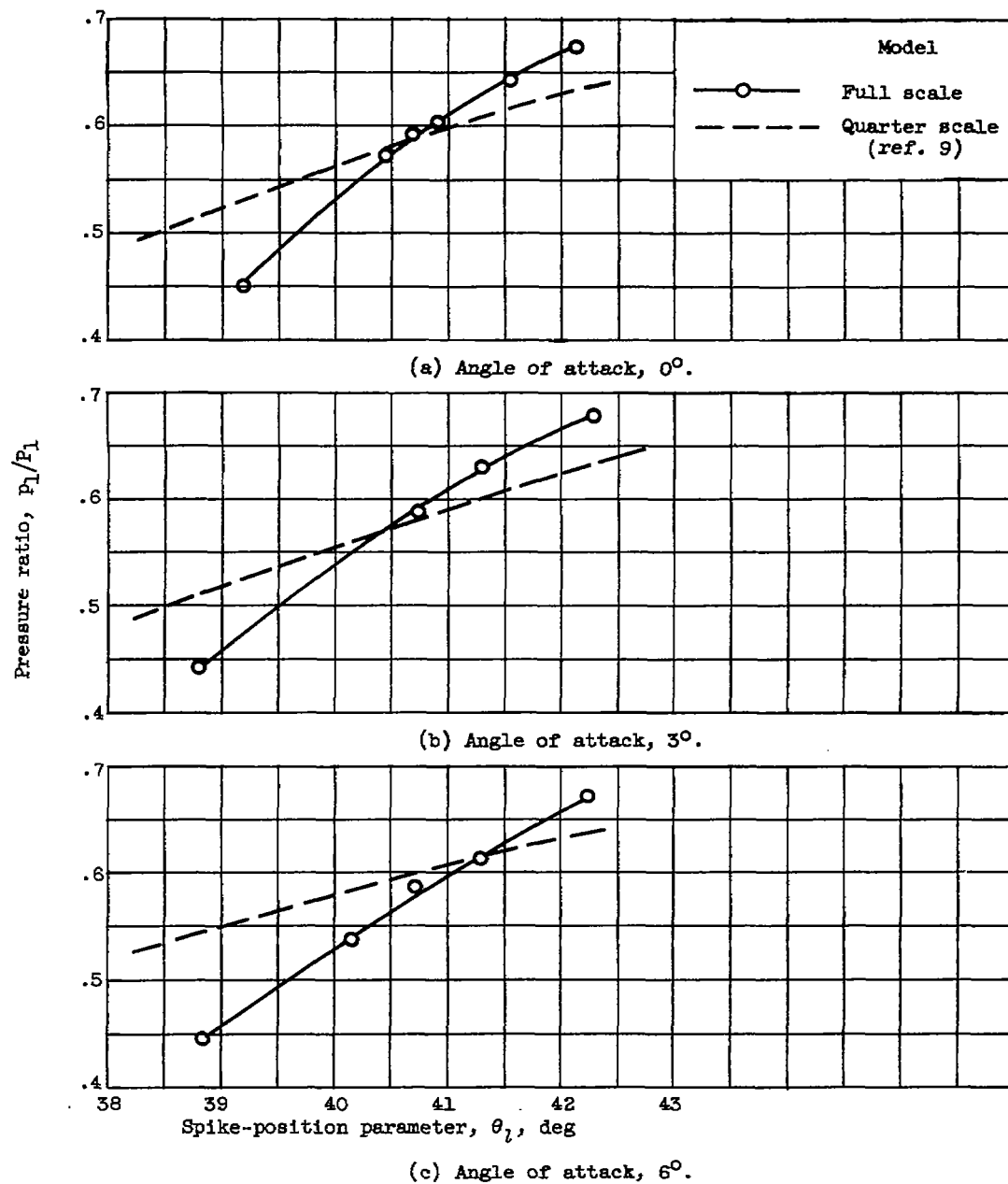


Figure 7. - Comparison of pressure signals from full-scale and quarter-scale inlet. Free-stream Mach number, 1.8; corrected airflow, approximately 151 pounds per second.

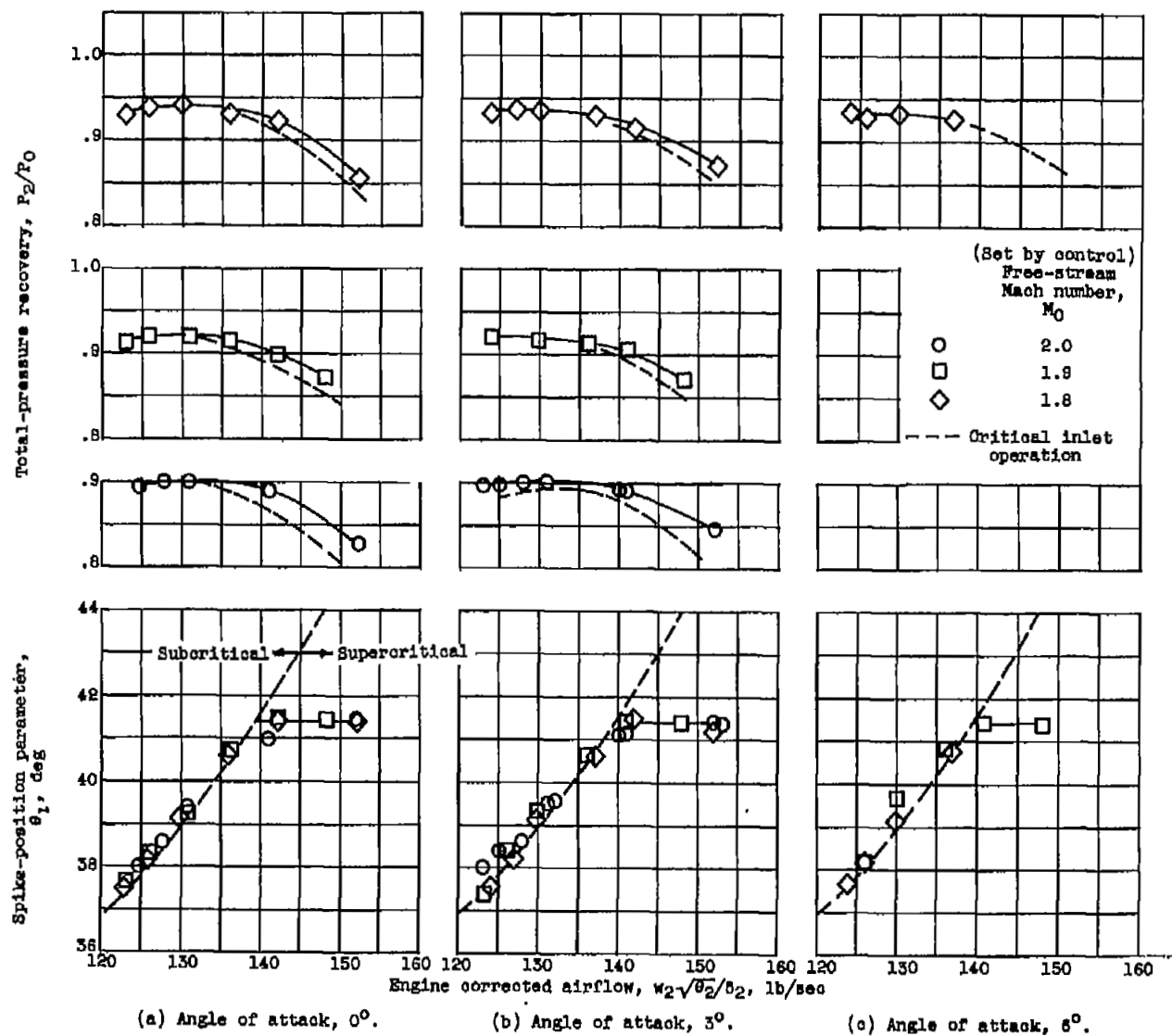


Figure 8. - Inlet performance set by control.

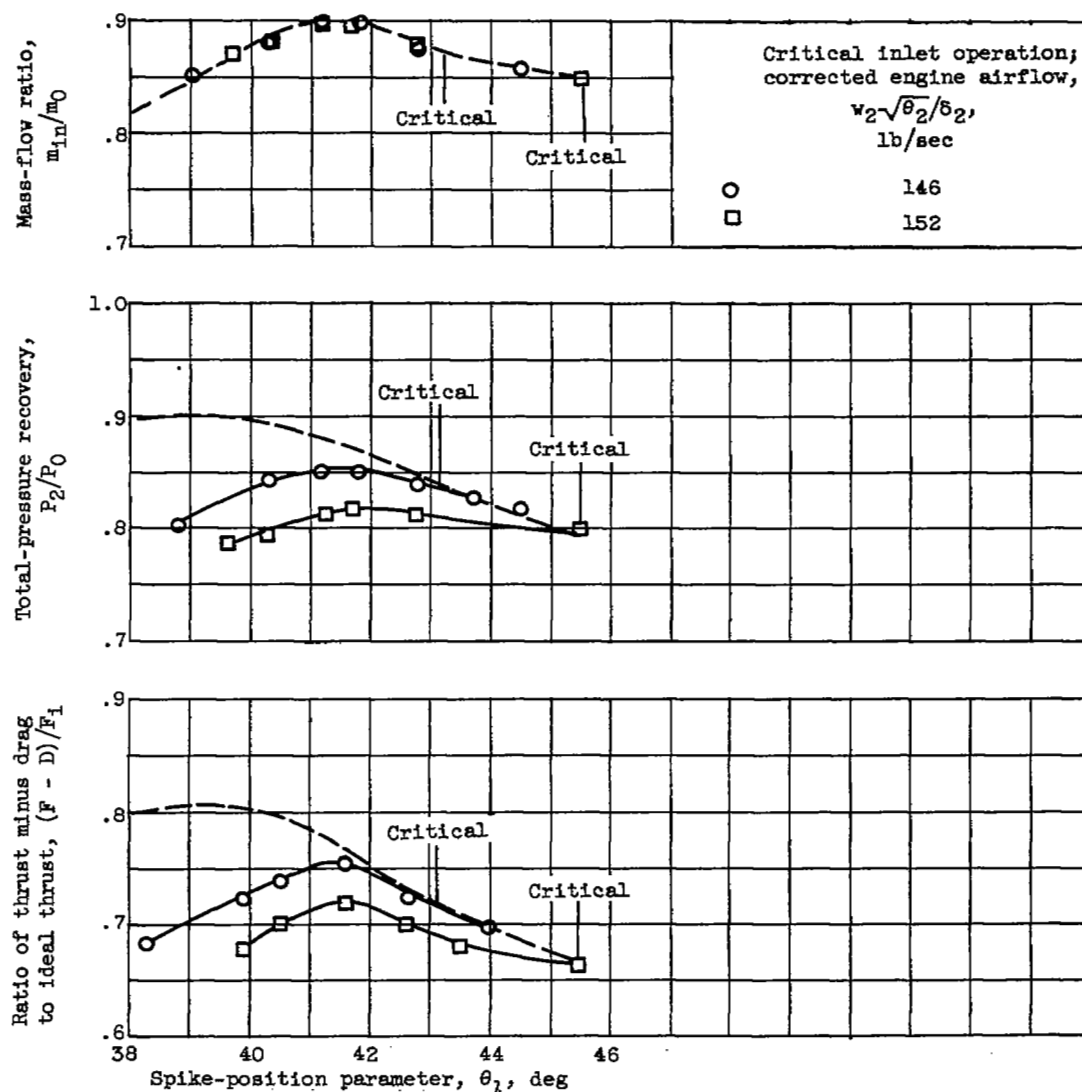


Figure 9. - Inlet performance at constant corrected engine airflow. Free-stream Mach number, 2.0; angle of attack, 0° .

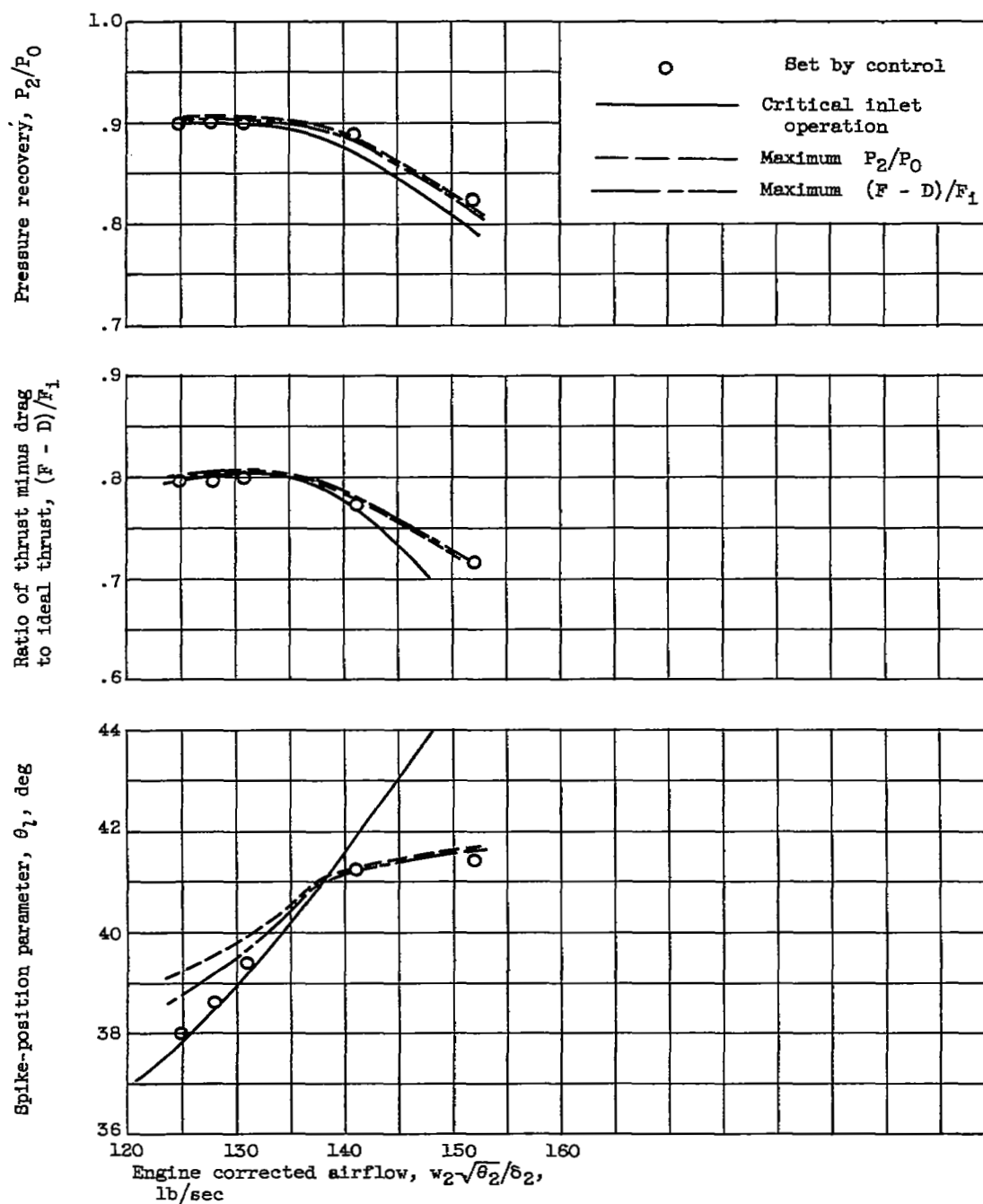


Figure 10. - Comparison of peak inlet performance with performance set by control. Free-stream Mach number, 2.0; angle of attack, 0° .

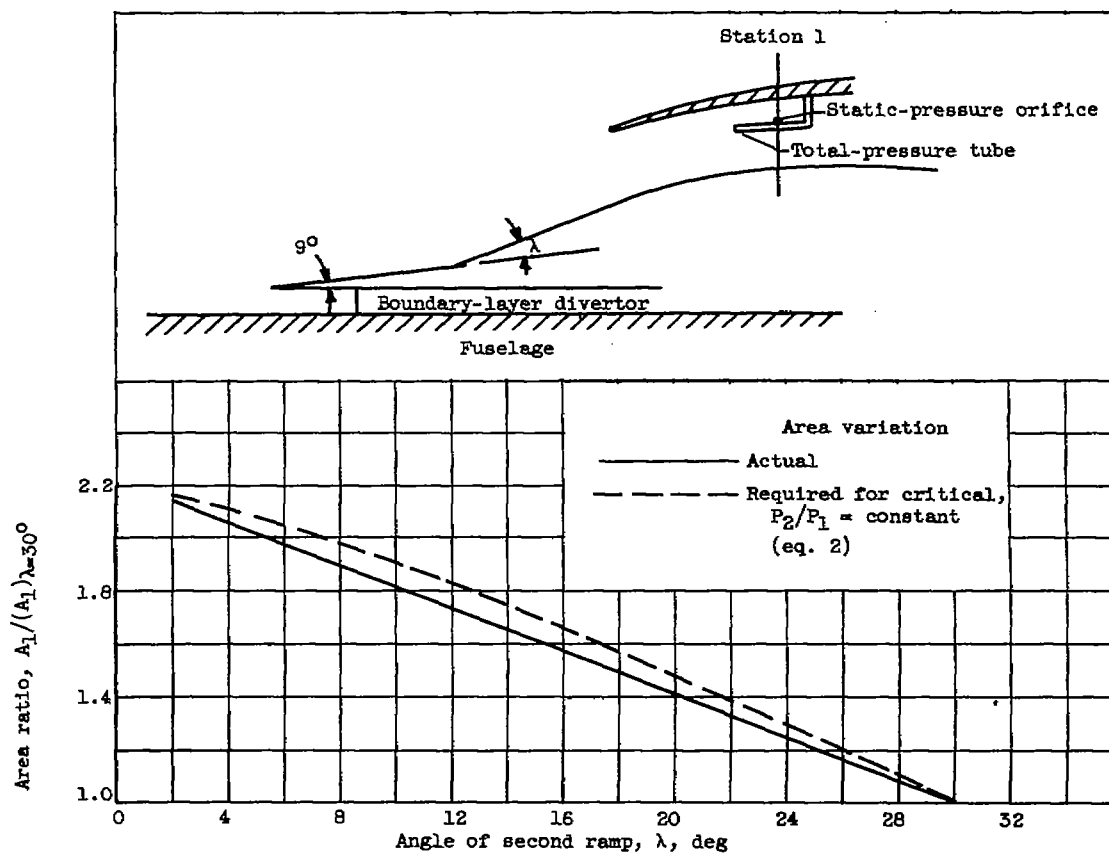


Figure 11. - Characteristics of area variation at sensing station for two-dimensional inlet configuration.

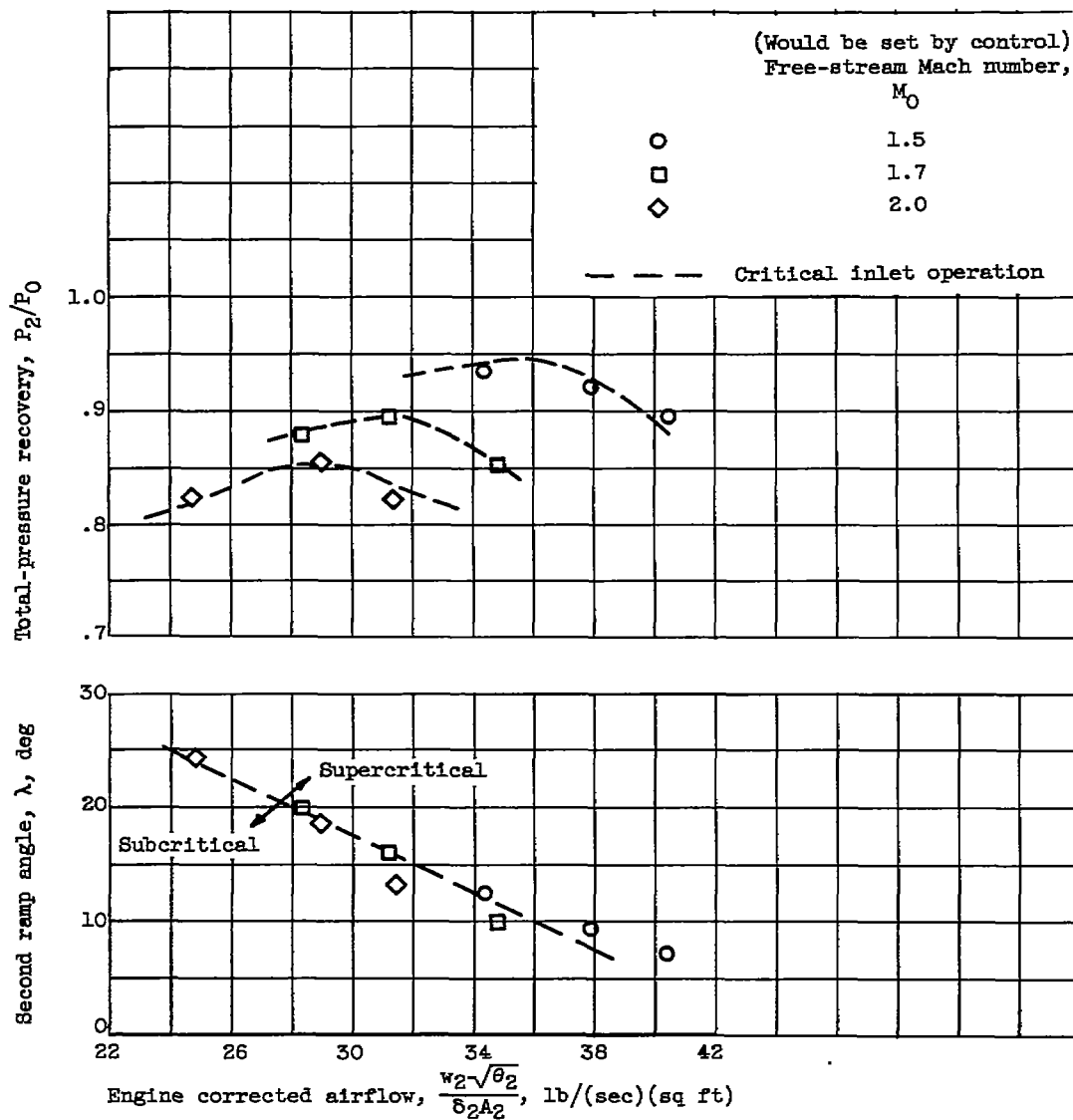
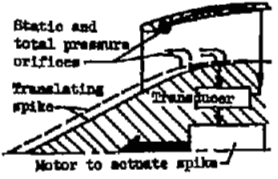
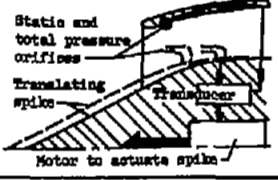
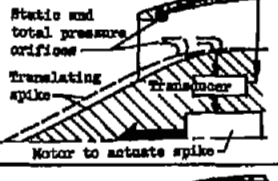
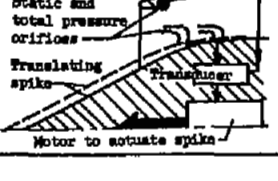


Figure 12. - Inlet performance which would be set by constant Mach number control for two-dimensional inlet configuration.

NOTES: (1) Reynolds number is based on the diameter of a circle with the same area as that of the capture area of the inlet.

(2) The symbol * denotes the occurrence of buzz.

Report and facility	Description			Test parameters				Test data				Performance		Remarks
	Configuration	Number of oblique shocks	Type of boundary-layer control	Free-stream Mach number	Reynolds number $\times 10^{-6}$	Angle of attack, deg	Angle of yaw, deg	Drag	Inlet-flow profile	Discharge-flow profile	Flow picture	Maximum total-pressure recovery	Mass-flow ratio	
CONFID. RM E57002 Lewis 10-by 10-ft supersonic wind tunnel		1	None	1.8	7.0	0,3,6	0					0.94	0.82	The principle of operation and the performance of a full-scale inlet control is presented. A concept of constant subsonic diffuser Mach number was employed.
				1.9	7.0	0,3,6	0					.95	.86	
				2.0	7.0	0,3,6	0					.90	.90	
CONFID. RM E57002 Lewis 10-by 10-ft supersonic wind tunnel		1	None	1.8	7.0	0,3,8	0					0.94	0.82	The principle of operation and the performance of a full-scale inlet control is presented. A concept of constant subsonic diffuser Mach number was employed.
				1.9	7.0	0,3,8	0					.95	.86	
				2.0	7.0	0,3,8	0					.90	.90	
CONFID. RM E57002 Lewis 10-by 10-ft supersonic wind tunnel		1	None	1.8	7.0	0,3,6	0					0.94	0.82	The principle of operation and the performance of a full-scale inlet control is presented. A concept of constant subsonic diffuser Mach number was employed.
				1.9	7.0	0,3,6	0					.95	.86	
				2.0	7.0	0,3,6	0					.90	.90	
CONFID. RM E57002 Lewis 10-by 10-ft supersonic wind tunnel		1	None	1.8	7.0	0,3,6	0					0.94	0.82	The principle of operation and the performance of a full-scale inlet control is presented. A concept of constant subsonic diffuser Mach number was employed.
				1.9	7.0	0,3,6	0					.95	.86	
				2.0	7.0	0,3,6	0					.90	.90	

Bibliography

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